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SURVEYING AND GEOPHYSICAL MEASUREMENTS WITH INERTIAL ROTATION SENSORS

Donald H. Eckhardt
Air Force Geophysics Laboratory
Hanscom AFB, Massachusetts 01731

Abstract

Azimuth and astronomic latitude can be determined using inertial rotation sensors. New applications in surveying and geodesy appear as the accuracy of the determinations improve. Geophysical applications require high precision sensors operating in a carefully controlled environment. Useful determinations of polar wobble might be feasible by monitoring azimuth and astronomic latitude in geophysical observatories.

Introduction

The sensors of an inertial navigation system are its accelerometers for measuring specific forces and its gyroscopes for measuring inertial rotations and maintaining a coordinate system. Another type of sensor which is now being developed for the next generation of inertial navigation systems is the gravity gradiometer. All of these sensors also have applications for surveying and geophysics. Gravimeters are accelerometers which have long been important tools of geodesists and geophysicists. Probably the first measurement of the acceleration of gravity was that of Christian Huygens (1629-1695) who used a pendulum gravimeter. The first field measurements of gravity for geodetic purposes were performed in the Nineteenth Century and the technology of gravimetry has developed extensively since then. The first laboratory version of a gravity gradiometer, a torsion balance, was built by Baron Roland Eotvos in 1888. In 1898 Eotvos built the first field gravity gradient torsion balance and, over the next half century, a large number of field torsion balances were built commercially and used by exploration geophysicists. But the gyroscope, which is now just one of several kinds of inertial rotation sensors, has had scant use by surveyors and geophysicists. With the continued development of gyroscopes and other inertial rotation sensors, they are now coming to the attention of the earth scientists who can see many fruitful applications of inertial rotation technology to their investigations. The purpose of this presentation is to discuss some of the opportunities and limitations of surveying and geophysical measurements with inertial rotation sensors.

I shall limit the scope of this discussion to those applications in which the inertial rotation sensors are operated at observing sites that do not move with respect to the earth's surface. In their operations, the sensors may be "strapped down" to the earth or they may rotate about a fixed point (null-seeking, for example), but they do not change their geographic locations during an observation. This excludes the inertial positioning systems which were the principal subjects of the First International Symposium on Inertial Technology for Surveying and Geodesy which was held in Ottawa on October 11-14, 1977.[1] The sensor environment is more benign than for inertial navigation or positioning systems because it is not exposed to all the shakes and jitters of a moving base. On the other hand, for surveying field measurements the sensor may have to withstand fairly rough treatment during transport between observation sites and it will have to operate in the open where the climate is uncontrolled. Useful geophysical measurements can only be feasible in a carefully controlled laboratory environment.

Surveying Applications: Azimuth

Twenty-five years ago I spent part of a beautiful summer in Nova Scotia learning the elements of geological surveying. Our instructor, Prof. Roland Parks of MIT, was an experienced mining geologist; that explained his emphasis on the technique of establishing azimuth in a mine by "jiggling in". Our mine was a three story barn and our mine shafts were holes through the floors. We suspended a pair of plumb lines down a shaft and "jiggled in" a theodolite at different levels until the two plumb lines were superposed, or lined up. This, Prof. Parks told us, was how mining geologists and engineers carried an azimuth reference down into a mine. He told us, in fact, that there was no better way of determining an azimuth in a mine and that accurate surveying was very important in some mines such as the copper mines under Butte, Montana, where there were multiple claims and every now and then an inaccurately surveyed mine would be extended into a neighboring claim. When the owner of the neighboring claim discovered such an infringement there invariably resulted a big fuss and lots of litigation. The only thing that I found academically less rewarding than "jiggling in" that summer was wading through pages of surveying calculations using log tables. Thus I concluded that I would never "jiggle in" professionally, but that maybe I ought to combine a degree in mining geology with a degree in law and get rich from other people's bad azimuths. Had I followed the path of forensic geology, I might now be wealthy and ready to retire; and that would be none too soon because the Hungarian Optical Works now manufactures a family of gyroscopic theodolites, some of which are distributed in the West and all of which provide much better underground azimuths than "jiggling in". In the near future, azimuth determinations for surveying applications might be made using fiber interferometer rotation sensors which can be made compact, reliable, efficient and relatively inexpensive. Perhaps another kind of inertial rotation sensor will turn out to be more suitable for a field instrument but, however it is done, there are many needs, including down in the mines, for azimuth surveys.

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If an ideal inertial rotation sensor is at latitude ϕ of a rigid spherical earth, and it is aligned with its input axis level and in the plane of the local meridian (north-south), it will measure the rotation rate $\omega_e \cos\phi$ where ω_e is 1 ERU (earth rate unit) which is 360° per sidereal day or 15".04 per second of time. If the input axis is kept level and rotated through a right angle so that it is parallel to the equatorial plane (east-west), it will measure a zero rotation rate. If the precision of the sensor is $\Delta\omega$, then its resolution in finding the east-west direction (and, from that, any other azimuth) is $(\Delta\omega/\omega_e) \sec\phi$ radians. For example, at latitude 45°, a rotation rate sensor which is precise to 10^{-4} ERU could be mechanized to resolve azimuth to 30". The time it takes to make an azimuth measurement depends on the procedure, and there are many possibilities. (For instance, one sensor might rotate in gimbals seeking a null or two sensors with orthogonal level input axes might be used in a "strapped down" configuration with a microprocessor to calculate their orientation from their signals.) What is a reasonable time to allow for a measurement depends on how good the measurement must be. For some of the cruder measurements, anything more than a few minutes might be too long, while for a first-order geodetic measurement which conventionally requires two nights of stellar observations, a full day per measurement is tolerable.

One relatively low accuracy requirement for azimuth is the measurement of magnetic declination for the compass rose of navigational charts. In the contiguous United States, the declination changes secularly by up to about 5' per year (6' per year in Alaska); in Europe the maximum rate is about 10' per year. Because of these changes, there is little value in measuring true north more accurately than 1' for compass rose applications. The DMA GSS (Defense Mapping Agency Geodetic Survey Squadron) azimuth accuracy requirement for the compass rose is 1' to 2'. To arrive at the declination of an airfield, say, individual declination determinations have to be made at multiple sites because of local magnetic anomalies. Each determination consists of a measurement of true north and magnetic north, and the magnetic north measurement is much the easier one. Using inertial rotation sensors, these measurements could be conveniently done by an unskilled surveyor using a "black box" device. At the 1' to 2' level, inertial azimuths are much more reliable than magnetic azimuths, so, if a surveying instrument could be produced which measures inertial azimuth rapidly and accurately enough to compete with a magnetic compass, it would have many useful applications for reconnaissance surveys.

A surveying instrument which measures azimuth with an accuracy of 5" would have further applications. It could be used for mine surveying; it could be used for aligning the guidance system of a short range attack missile; it could be used for aligning aircraft navigational aids (e.g., ILS and VOR); and it could be used with electronic distance measuring equipment for making eccentric ties, for example, tying the top of a hill to a valley geodetic control point which has been established by satellite Doppler or inertial positioning surveys.

A surveying instrument which measures azimuth with an accuracy of 1" or better would be of great value to geodesists. For the GSS, first-order geodetic surveys have azimuth accuracies of 1".0 to 1".5 and second-order surveys have accuracies of 1".5 to 1".7. The most accurate astronomic azimuth that the GSS can now measure, and it requires great effort, is 0".6. At the Advanced Inertial Test Laboratory of the Central Inertial Guidance Test Facility at Holloman AFB, the azimuth requirement for 1987 is 0".2. With higher accuracies, the measurements become more difficult and more subject to cultural and geophysical disturbances.

Surveying Applications: Astronomic Latitude

The angle between the earth's rotation vector and its projection on the local level is the astronomic latitude. An inertial sensor with precision $\Delta\omega$ could be mechanized to resolve astronomic latitude to $\Delta\omega/\omega_e$ radians. The difference between the astronomic latitude and the geodetic latitude is the meridional deflection of the vertical, an angle that can attain 30" (equivalent to 925 m) in a few regions. Polar explorers measured the astronomic latitude to find the North and South Poles but, because of the variable deflection of the vertical, there is little requirement by most surveyors for astronomic latitude. Astronomic latitude is principally of interest only to physical geodesists, geophysicists and astronomers. Geodesists can measure astronomic latitude with an accuracy of 0".3, but there are needs for easier or more accurate ways of determining astronomic latitude. Along the high speed test track at Holloman AFB, for example, astronomic positions (latitudes and longitudes) and their corresponding deflections of the vertical are accurate to 0".3; the requirement for 1987 is 0".1. DMA and the Air Force Geophysics Laboratory are now supporting a research and development program to build a two color refractometer that will be able to measure astronomic refraction to 0".1. Our goal is to be able to compensate for astronomic refraction in astronomic position measurements, especially for measuring astronomic latitude. Such an instrument would probably not be needed if we could measure astronomic latitude to 0".1 inertially.

Geophysical Applications: Polar Motion

The earth's pole of rotation wobbles, nutates, precesses and wanders[2] and these motions are observable by optical astrometry, lunar and artificial satellite laser ranging and VLBI (very-long baseline interferometry). Geophysicists are particularly interested in the wobble and nutation because their characteristics (e.g. the wobble spectrum and nutation amplitudes) provide us information concerning the elasticity of the earth's mantle and fluidity of the earth's core. Sufficiently sensitive inertial rotation sensors could be used to measure polar motion by tracking azimuth and astronomic latitude from one or more fixed geophysical observatories.

Where inertial rotation sensors might best contribute is in measuring the wobble whose spectrum has a sharp peak at 12 months (annual wobble) and a broad peak centered at 14½ months (Chandler wobble); the wobble amplitude runs to about 0"3. A more difficult goal would be to measure the near diurnal nutation which has an amplitude of 0"01. The best alternate approach is VLBI which likely will soon have a pole positioning capability of about 0"003. To match the VLBI capability, an inertial rotation sensor would have to be precise to about 10^{-8} ERU.

At 10^{-8} ERU there are a number of difficulties to overcome in separating true polar motions from apparent polar motions which are caused by local effects.[3] First of all, the pier on which the instrument rests might rotate. At a Massachusetts inertial component testing facility the astronomic azimuth of a reference cube on a pier anchored to bedrock was observed to vary with an annual period, a few months out of phase from the mean annual air temperature. The annual range was about 5". The rotation has been ascribed to thermal and insolation effects of the local topography and the building. If the pier can be set in a deep vault so that it does not rotate significantly with respect to the surrounding rock, then the whole region might rotate secularly; a rotation of at least 0"003 per year is geophysically quite admissible and, in some locations, very likely.

Any periodic or transient local tilting about an east-west axis appears to the sensor as a component of rotation perpendicular to the earth's rotation pole; the signal is identical to that of a temporal change in azimuth. For the periods of interest the tilt rate of the sensor platform must either be kept less than 10^{-8} ERU or it must be monitored that precisely. Semidiurnal tidal tilts of the earth's crust have rotation rates of the order of magnitude 10^{-7} ERU. A measurement of tilt relates the surface of a pier or platform to the vertical, but the vertical varies at tidal periods with respect to the mean vertical which is the required reference for relating to inertial space. The semidiurnal vertical variations are almost as large as their corresponding tidal tilts but they are of opposite phase. Diurnal vertical variations are almost as large as semidiurnal variations, but diurnal tilts are relatively small. Neither the tidal tilts nor the vertical variations are easily predictable, especially near the coast where the ocean tides result in periodic loading and flexing of the crust and mass attraction variations. Only the very best tiltmeters in the best installations can marginally measure diurnal and semidiurnal tilting with a precision of 10^{-8} ERU. The diurnal and semidiurnal variations can be measured astrometrically, but not to 10^{-8} ERU.

Because of tidal problems, measuring near diurnal nutations with inertial sensors appears infeasible. Nevertheless, with sufficient care, and a 10^{-8} ERU rotation sensor, measuring the annual wobble and Chandler wobble with 0.1% resolution appears feasible.

Other Geophysical Applications

There aren't any good ones that I can think of. Combining measurements of tilt from tilt meters with measurements of tilt plus vertical variation plus nutation from inertial rotation sensors can give vertical variation plus nutation. There is no semidiurnal nutation, so the semidurnal vertical variation could be resolved, at best, to about 10% using a 10^{-8} ERU sensor. VLBI will soon be able to measure the length of a day, week, month or year to 0.1 ms. For one day, that is 10^{-9} ERU; and for one year that is 3×10^{-12} ERU. An inertial rotation sensor with a vertical input axis would have to resolve roughly 10^{-11} ERU to detect torsional seismic modes caused by major earthquakes. I invite your suggestions of any applications that I may have overlooked.

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